NASA/CR- 1998- 208132

IN-18-CR
134050

AIAA-98-1929

X-33 / RLV
Reusable Cryogenic Tank VHM Using Fiber Optic Distributed Sensing Technology

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Conf. Paper

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Abstract

The reusable oxygen and hydrogen tanks are key systems for both the X-33 (sub-scale, sub-orbital technology demonstrator) and the commercial Reusable Launch Vehicle (RLV).

The backbone of the X-33 Reusable Cryogenic Tank Vehicle Health Management (VHM) system lies in the optical network of distributed strain, temperature and hydrogen sensors. This network of fiber sensors will create a global strain and temperature map for monitoring the health of the tank structure, cryogenic insulation, and Thermal Protection System. Lockheed Martin (Sanders and LMMSS) and NASA Langley have developed this sensor technology for the X-33, and have addressed several technical issues such as fiber bonding and laser performance in this harsh environment.

Introduction

Launch vehicles of the future will be developed and operated within strict economic constraints. A key driver to the successful commercial deployment of the Reusable Launch Vehicle (RLV) will be reducing the cost of operations. A team of Lockheed Martin companies and NASA Langley have been working on a demonstration on the X-33 Advanced Technology Demonstrator (ATD) Vehicle of the capabilities of fiber-optic based sensors to monitor the structural integrity of large composite structures. On the X-33, the Distributed Temperature Sensor (DTS) fibers are located on both the X-33 LO_2 and LH_2 tanks, while the Distributed Strain Sensor (DSS) and Distributed Hydrogen Sensor (DHS) fibers are located only on the LH_2 tanks. The optics and processing electronics are housed in the Avionics bay in a VME chassis as shown in Figure 1.

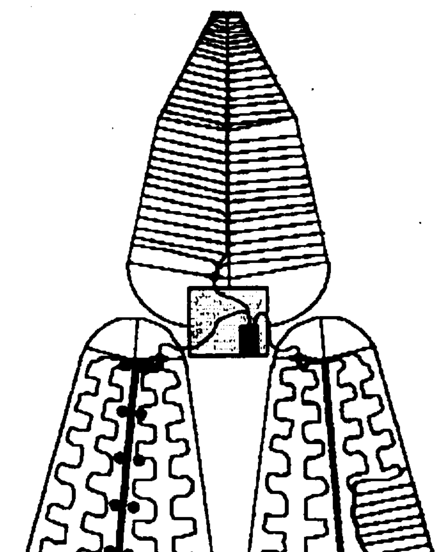

Figure 1. Distributed network of sensors for monitoring strain, temperature, and hydrogen on the X-33 tanks

The intent in designing these systems was to prove the viability of fiber optic sensors in a flight environment to transfer the technology to the RLV. COTS technology was used as much as possible to reduce the cost and schedule time. The DTS, designed under subcontract by SPEC Inc., uses standard 62.5μm core multimode communication fibers epoxied over the cryogenic tank insulation as the sensor elements, and a distributed anti-Stokes Raman thermometry technique to process the signal.[1] The strain/hydrogen sensors of the DSS are 9μm core single mode distributed Bragg Grating fibers epoxied along the composite LH_2 tanks' dual lobe joints. A thin palladium coating applied to the Bragg Gratings induces a strain on the grating when exposed to hydrogen, creating a hydrogen sensor which uses the same processing as the strain sensor system. NASA Langley Research Center (NASA/LaRC) initially developed and prototyped the DSS processing technique,[2] and the flight-worthy design is currently being implemented by Sanders, a Lockheed Martin Company. This paper describes the design technology and issues of fiber optic sensor bonding and the DSS optics and electronics.

Design Technology

Fiber Optic Tank Bonding

The implementation of the fiber optic sensors to the tank structure is crucial to the overall system performance. There has been much effort to embed fiber optics in composite structures, but with a structure that will be exposed to the extremes that the cryogenic fuel tanks will experience. Due to this, it was determined that the fiber optic sensors would be bonded to the surface of the tank and over the cryogenic insulation.

LMMSS developed adhesives and bonding techniques to accomplish this. The task of bonding required that the adhesives be able to accommodate the changes in the temperature from the low to the high ranges. The three (3) fiber sensors had different requirements. The temperature sensor required that the fiber have a good thermal conduction path to sense the temperature changes. The hydrogen leak detection required that the Bragg Gratings be isolated from mechanical strain so it does not influence the measurement. Finally, the strain measurement required that there be good strain transfer to the Bragg Gratings and that Coefficients of Thermal Expansion (CTE) not influence the measurements.

With these requirements LMMSS developed special adhesives. These adhesives were applied during a ground test of a composite cryogenic tank. A DSS single mode fiber was applied to the tank by bonding the Bragg Gratings with an adhesive that had a good CTE match to the composite structure. The rest of the fiber was bonded with another adhesive that minimized strain transfer as not to induce false readings. In future applications a resilient adhesive should be used to further reduce the strain transfer in non sensor locations. This bonding of the DSS is shown in Figure 2.

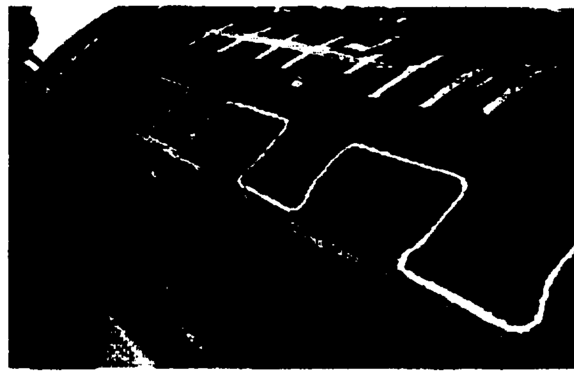

Figure 2. Distributed optical fiber strain sensor bonded to composite liquid hydrogen tank. The single fiber makes 20 biaxial strain measurements.

The bonding of the DTS was done using another adhesive which provided the required thermal conductivity to make the sensor effective. The bonding of this sensor was much less critical than the DSS. The installed DTS is shown in Figure 3.

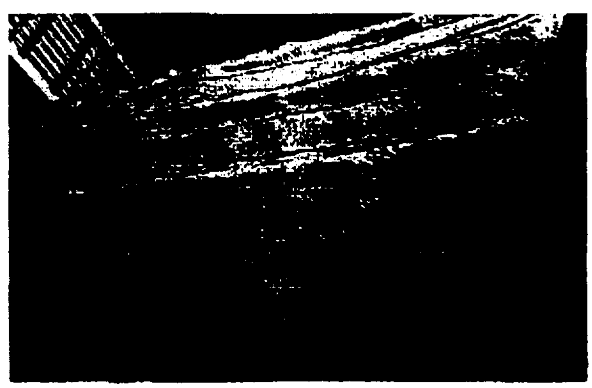

Figure 3. Distributed optical fiber temperature sensor bonded to cryogenic insulation. The single fiber makes 50 temperature measurements.

The lessons learned from this effort include the proper bonding of various fiber optic sensors and how to critical the bonding is to the sensor performance.

Optics and Electronics DSS

The DSS monitors the change in the resonant wavelength of each Bragg grating, λ_B, caused by the applied strain. It employs a wavelength scanning source or a tunable laser to acquire the sensors' reflected spectral response. Back-reflected sensor data is digitized, sampled, wavelength tagged by a reference interferometer, and Fourier methods are used to recover the reflected center wavelength of each grating. Shifts in the resonant wavelength occur due to the applied strain and temperature, as represented by the following equation:

$$\Delta\lambda_B / \lambda_B = (1-p_e)\Delta\varepsilon + (\alpha+\xi)\Delta T \qquad (1)$$

where $\Delta\varepsilon$, the applied strain change, is assumed uniform over the grating length, ΔT is the temperature change, $p_e \cong 0.204$ is the effective elasto-optic coefficient, $\alpha \cong 0.55\times10^{-6}$ /K is the thermoelastic coefficient, and $\xi \cong 8.3\times10^{-6}$/k is the thermo-optic coefficient.[3]

While fiber optic distributed sensing systems have been demonstrated in the laboratory, moving this technology to flight vehicles has imposed many design constraints and challenges. For instance, all of the electronics must be designed so as to operate in an extremely rugged vibrational environment where the temperatures can be as high as 85 or as low as -15 degrees Celsius. Furthermore, as can be seen above, the applied strain is related to both the temperature and the mechanically induced strain experienced by the structure. The X-33 tanks are expected to undergo wide temperature variations from roughly ambient to cryogenic conditions. The expected strain/temperature range for the X-33 LH_2 tanks is equivalent to -3200 to 3800μm, corresponding to an 8.5nm wavelength tuning range. Correlation with conventional strain and temperature sensors will determine the system accuracy and provide calibration for isolating strain. Several of the requirements driving the design of the DSS and DTS listed in Table 1. The strain range, measurement frequency, length of the sensors, and number of sensors have a direct relationship with the laser tuning range, tuning speed, linewidth and power requirements, respectively.

Number of sensors:	20
Strain measurement frequency:	0.5 Hz
Sensor length:	20 feet
Conduction cooled VME electronics	
Vibration:	0.05 G2/Hz
Card-edge temperature:	-18 to 85°C
Number of VME modules	2 (slots)

Table 1 - DSS Requirements Summary

A block diagram of the DSS is shown in Figure 4. It consists of a tunable laser(s), a wavelength tagging Michelson interferometer, an optical distribution network, optical receivers, and a digital signal processor. The biggest change from the original NASA prototype was in the technology of the tunable laser(s). NASA used an external cavity mechanically tuned laser employing a rotating reflective grating as the wavelength tuning and selection device. After analysis of the rotational and translational parameters (dl/dq, dl/ds) governing a typical system, it was ascertained that these type of devices could not be used in the X-33 environment due to their susceptibility to mode hopping during vibration.

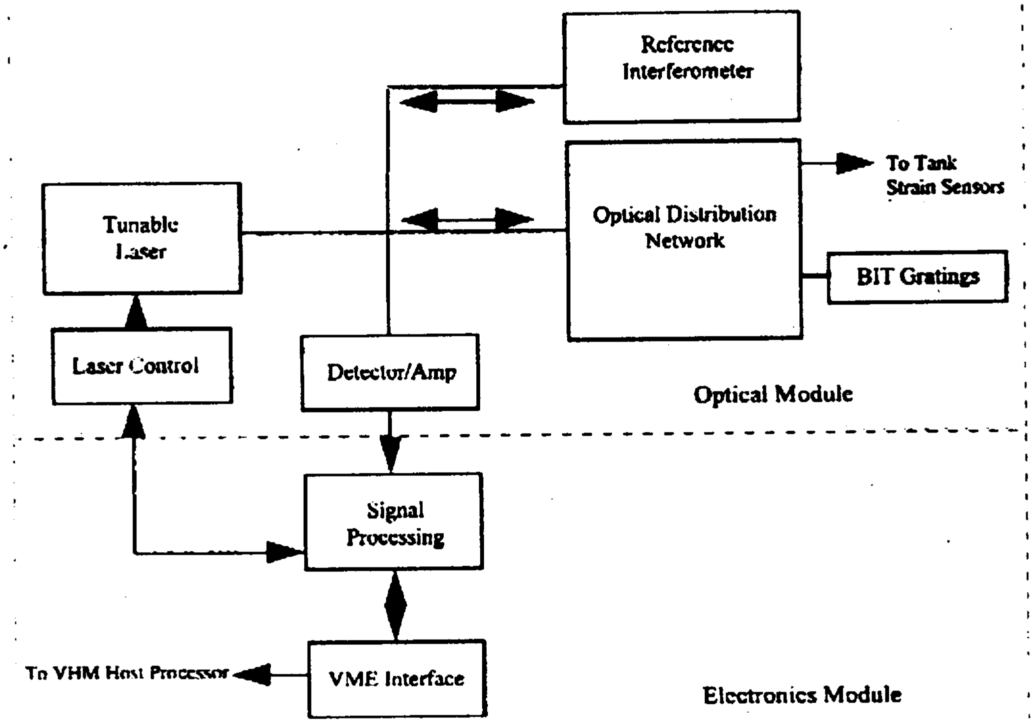

Figure 4. DSS Block Diagram

Use of a tunable fiber laser was also investigated, and is still under investigation by NASA/LaRC. It would have certainly provided the wavelength tuning range required, as has been previously demonstrated,[4] but it would not meet the tuning speed requirement. In order to provide a single mode output, the fiber laser length needs to be less than 3cm, and it must be tuned by external stretching of its cavity length. Further technological improvements were needed to reduce the vibration effects on the mechanical tuning mechanism.

Because vibration effects had appeared to have ruled out other technologies, laser diodes were investigated. Of the two types of electronically tunable laser diodes that exist, the Distributed Bragg Reflector (DBR) lasers have a wider tuning range (~4nm) than Distributed Feedback (DFB) lasers (~2-3nm), and neither are commercially available. The development of these lasers is still in the research and development phase, and are known to be manufactured by research centers only. One such center has begun to develop commercial DBR lasers for the telecommunications industry, and is supplying DBR lasers for the X-33 DSS. This is expected to be the first time that a DBR commercial laser, normally packaged to meet Bellcore TA-NWT-983 specifications, will be subjected to a harsh flight environment such as that of the X-33..

A DBR laser is a semiconductor laser which uses a phase tuning section and a tunable Bragg reflecting section for wavelength tuning and selection, respectively. Its operation is analogous to the external cavity tunable laser, but the laser is tuned electrically by varying the current to each section. The current alters the carrier concentration or refractive index, and hence the optical length of the medium. The expected 4nm tuning range made the use of two of these devices ideal for the X-33 DSS system. There are performance issues that are still being investigated. They include the effects of phase noise, linewidth broadening, lifetime with increased tuning current, temperature limitations and cooling mechanisms. Some of these will be discussed later.

The Michelson interferometer design evolved from a fiber optic Fabry-Perot cavity. NASA/LaRC replaced the cavity with a Michelson interferometer using Faraday rotator mirrors when it exhibited polarization fading. The cavity length was originally twice the length of the longest sensor (~20x2 feet) to allow for

Nyquist sampling, but it was decreased to the same length in order to reduce the coherence length (linewidth) requirement of the laser.

In an attempt to maintain the COTS nature of the experimental system while incurring minimal risk, the optical distribution network was designed using a commercial 2x32 waveguide coupler and several 1x2 fused fiber optic couplers. On the other hand, custom photodetectors were used to obtain maximum sensitivity, since the expected return levels were not known. This lack of information still represents a risk to system performance.

Sanders has chosen to use the Analog Devices Quad SHARC for the heart of the signal processor since this COTS signal processor allowed a maximum reuse of previously developed software and the type of increased flexibility that a technology demonstration program requires. Each of the 40 Mhz. SHARC signal processors is rated to provide a sustained 60 MFLOPS of processing power and the architecture is particularly optimized to support the Fourier processing that underlies the DSS operations. The DSP can also accept information and commands from the host processor and the laser controller and receiver circuitry, thus acting as the central controller for the DSS. A multi-chip module with four signal processors is available that is capable of operating in the temperature regime imposed by the X-33 flight test environment.

Issues

There are general issues or constraints imposed by the X-33 VHM chassis and environment which affected the DSS design, and there were specific component issues. Only a limited amount of VME board space existed on 2 modules. This directly influenced the number of sensors (optical receivers) that could be measured. To keep the receiver circuitry (photodiodes, transimpedance amplifiers, multiplexers, ADC) on one CCA, the number of sensors was reduced to 15. We have chosen to locate the passive optical components on the cover of the Optical Module to facilitate assembly. The limited bend radius of single mode fibers are expected to cause fiber routing restrictions and determine the layout of the optical components. All splices will be re-coated with acrylate to avoid mechanical support and conserve space.

The procurement of commercial lasers with a built-in thermo-electric coolers (TECs) will be the limiting factor in the operation of the DSS over temperature. The maximum acceptable card edge temperature of 85°C may occur only after landing when the X-33 cooling system shuts down for a short period of time, however, the X-33 temperature regime is not known with any certitude. Therefore, the DSS may be operational during only certain phases of the flight test profile. The optical distribution network is comprised of fused fiber couplers and planar waveguides. Both are rated for the same highest operational temperature (~+85 °C). The limiting factor in the fused fiber devices are the epoxies used to provide strain relief. However, one can work with vendors to specify the use higher temperature curing epoxies if necessary.

The strain measurement frequency (laser sweep speed) and sensor length (modulation) will create a backreflected signal that is expected to have frequency components up to 4MHz. Since the DBR has a non-linear wavelength response to a linear drive current, the laser drive needed to be divided into segments which would produce piecewise linear wavelength outputs. Fourier transform processing required that these segments be equal in length. Laser output power also fluctuates with laser drive current, and therefore the digitized measured samples of the sensor response waveforms needed to be compensated for power.

Careful attention was paid to the noise and linearity of the laser drive design. Non-linearities and noise can cause the laser to produce a non-monotonic wavelength output which would create jumps in the wavelength tagging signal, and thereby corrupt the acquisition process of back-reflected data. Sanders has developed a method of tuning DBR lasers which produces a monotonic wavelength response.

As the tuning currents to each laser increases, so does the linewidth. In order to accept the linewidth performance of the lasers, the processing had to be changed from the original NASA baseline of using the wavelength tagging signal directly for Nyquist sampling, to interpolating the wavelength tagging signal. This was accomplished by reducing the Michelson interferometer Δl. This also helped reduce the mode-hopping sensitivity of the wavelength tagging clock, and reduced the laser drive noise and linearity requirements.

Mechanical isolation of the lasers was considered, but limitations in board space made this impossible. The risk is currently being mitigated by vibration testing of a representative laser.

By far the most challenging aspect of the DSS design is the use of an interferometer for wavelength tagging. Any type of interferometer is extremely sensitive to vibration as well as temperature changes. Sanders is currently developing a method to allow the use of a fiber optic interferometer on the X-33 by implementing a combination of mechanical isolation and processing techniques to reduce the interferometer's susceptibility to vibration.

Summary

Valuable lessons have been learned in the development of the X-33 fiber optic distributed sensors. Preliminary work has been carried out to identify and characterize bonding techniques for cryogenic composite structures. A new method/circuit for driving DBR lasers has been developed which produces a piecewise-continuous monotonic wavelength response. Processing techniques are currently being developed to lessen the impact of temperature and vibration effects on the interferometer for this particular design. Some technological improvements are still needed in the area of expanding the temperature range of optical receivers and TE coolers.

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